TRANSFORMER PROTECTION

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I. <u>Introduction and Recommendations</u>

This paper is a review of the factors involved in the protection of distribution transformers against lightning surges and short circuits, and related problems. Information on these subjects is re-examined in an attempt to determine the proper protective equipment necessary. No attempt is made to show that the arrester is superior to the open gap or vice versa.

It is recommended that where transformers are now protected by open gaps that the total gap air space be shortened and that transformer manufacturers be contacted to provide closer gap spacings in the future. It is also recommended that the spacings on expulsion type arresters be lessened, and that consideration be given to specifying higher impulse test requirements on 7.2/12.45 KV transformers than proposed A.S.A. requirements. It is further recommended that consideration be given to the greater use of internally fused transformers with secondary protection.

II. <u>Insulation Protection</u>

A. <u>Standard Testing Methods and Volt-time Curves</u>

Before embarking upon a discussion of insulation levels, it might be well to review insulation testing recommendations and impulse wave definitions.[1] The Proposed American Standards for Transformers, Regulators and Reactors[2], state that "the standard impulse wave is a 1.5 x 40 microsecond wave. This is an impulse for which the time from start to crest is 1.5 microseconds ± 1 microsecond and the time from start to half crest value on the tail is 40-50 microseconds." The time zero is determined by drawing a line through the 0.1 and the 0.9 crest values, and extending it to the zero axis at point O_1.

The time to crest is considered as 1.5 times the time between the 0.1 and the 0.9 crest values. In the figure below E represents the crest value, O_1t_1 is the time to crest, and O_1t_4 is the time to half value. O_1t_1 is considered as $1.5 \times (O_1t_2 - O_1t_3)$.

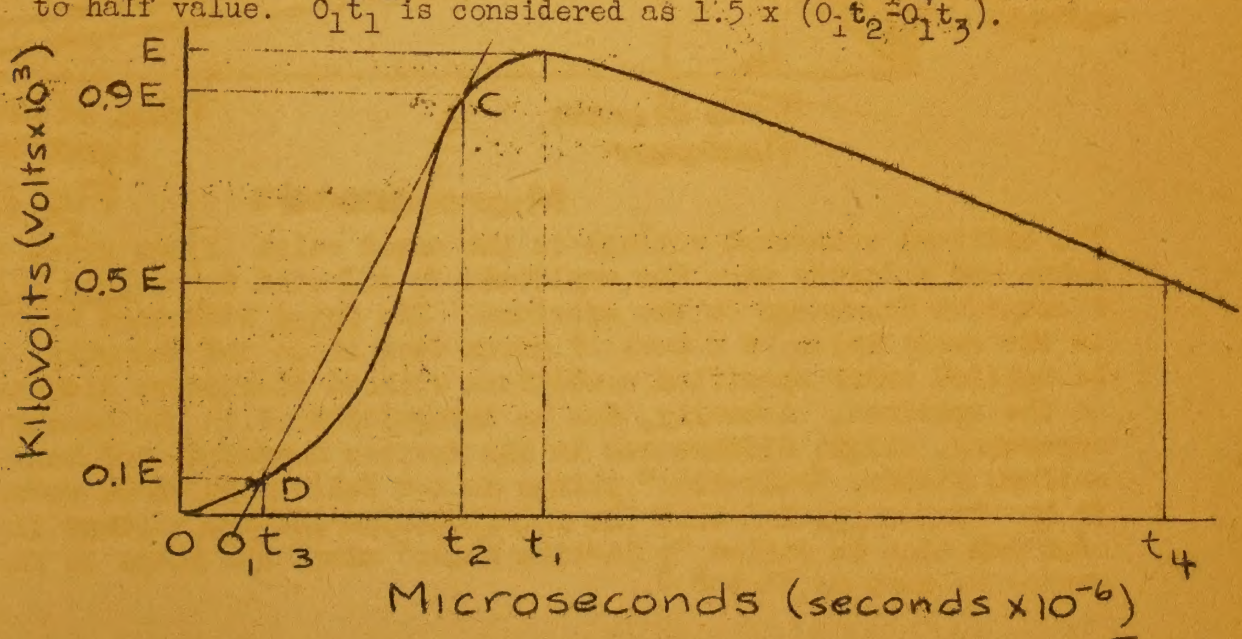

Fig. 1.

H6 bldg

The "effective" rate of rise of the front of the impulse is taken as the slope of the line DC. In some cases, the tangent to the upper part of the impulse wave is taken as the rate of rise. (Measurement of "Rate of rise" has not as yet been standardized.) It can be seen that the slope or rate of rise of the impulse will vary depending on the crest value.

A flashover, or a disruptive discharge may take place when testing an insulation specimen with an impulse. When such a discharge occurs, a "chopped wave" results; this chopping may occur on the tail, at the crest, or on the front of the wave. If no discharge occurs, a "full wave" results. The critical flashover voltage of a test specimen under an impulse of a given wave shape and polarity is the crest value of that impulse when its amplitude is adjusted to cause flashover on 50 percent of the applications. If impulse waves with various rates of rise are applied to piece of apparatus, and a curve drawn with the flashover points, where flashover occurs on the front, and the crest voltage values, where flashover occurs on the tail, as ordinates, and with time to flashover as absicissa, a "volt-time" curve results. Fig 2 is such a curve, with the A.I.E.E. recommended terminology.

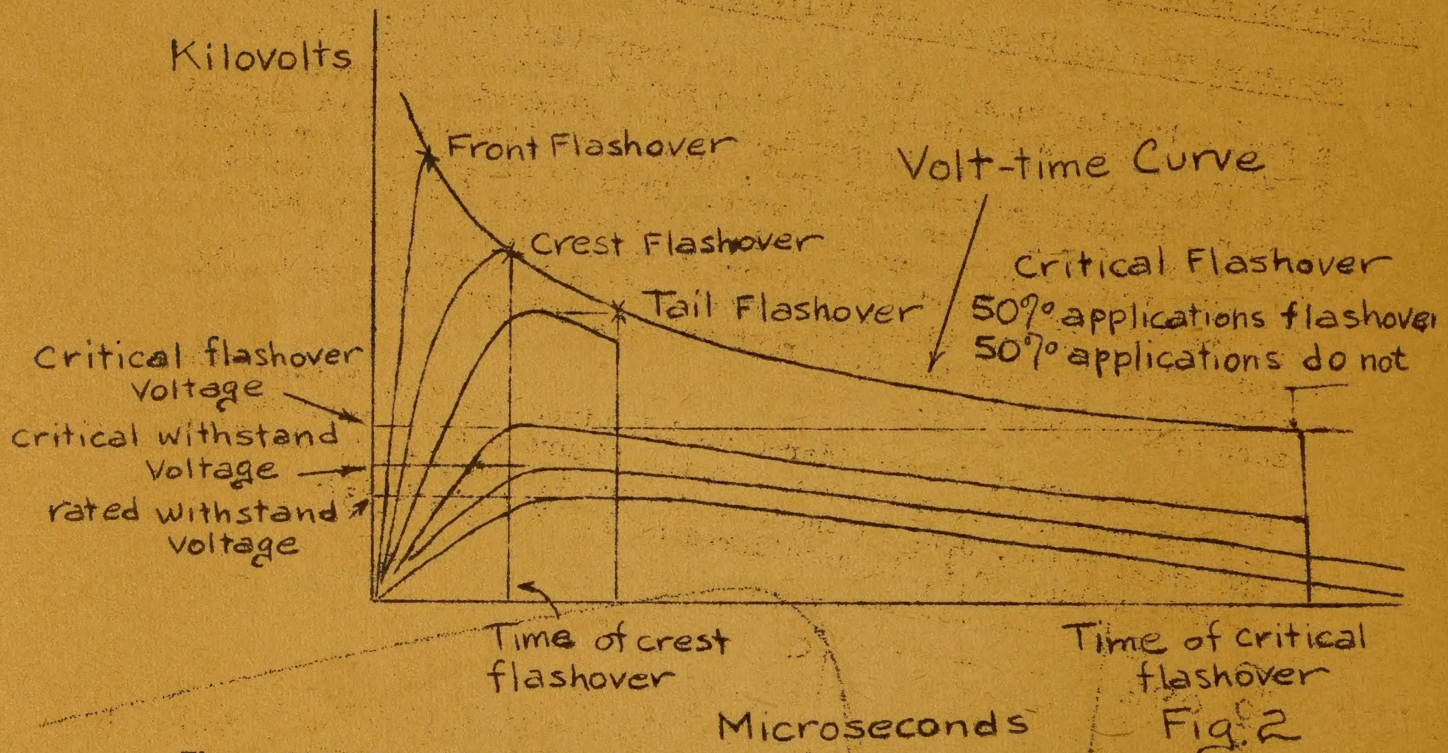

Fig. 2

The critical withstand voltage is the crest value of any given wave shape and polarity when the amplitude is adjusted to be just below disruptive discharge on the specimen. The rated withstand voltage is the crest value of a wave of given wave shape and polarity, to be applied under specified conditions without disruptive discharge on the specimen. Actually, due to irregularities in the measuring apparatus, slight differences in the devices measured, and non-uniform fields, "volt-time" points do not fall on an exact curve. It has been suggested that the relationships between voltage flash-over and time be called "volt-time areas" since the range in flashover varies as much as 30-40%.3

It can be seen that the time to flashover depends on the slope of the wave (assuming all waves are the same shape) and that the flashover voltage increases for short times.

B. Transformer Insulation Requirements

Transformers for 7.2/12 45 KV systems presumably meet A.S.A. proposed standard insulation tests for 15-KV insulation, as these standards are accepted by the electrical industry. At the present time, these specified impulse tests are, (1) - two 110-KV chopped waves with flashover within a minimum time of 1.8 microseconds and, (2) - a 95-KV full wave withstand. The chopped wave test is usually made by flashing over the bushing or an external rod gap.[2]

It has been very difficult to obtain authoritative data on the shape of the transformer insulation volt-time curve. The two main reasons are the large number of tests necessary to obtain satisfactory data and the difficulty in measuring voltage and time and in controlling discharge for times under 1 microsecond. From the A.S.A. standards, only two points on the curve are known, or rather it is known that the insulation volt-time curve lies above these two points. Some manufacturers claim much more insulation than others. In fact one manufacturer claims 150-KV full wave insulation for 7.2/12.45 KV transformers. We can be reasonably sure that most reputable manufacturers would supply an insulation margin above the required values; however, none of them will furnish any guarantee to that effect without a price increase. Hence it is only certain that the transformer insulation values meet the A.S.A. requirements.

Figure 3 indicates the volt-time curve shapes for transformers given by two manufacturers, with the known point at 110 KV, 1.8 ms. It can be seen that these shapes vary widely, even though both would meet A.S.A. requirements.

Also shown are the volt-time curves of: a 9-KV expulsion type arrester, a 2" rod gap (cut to standard N.E.M.A. dimensions), a double gap with two 7/8" air gaps, a 9-KV valve type arrester and a bushing for 7.2/12.45 KV transformer. It should be noted that these curves (except for the transformer lower limits) represent average points; deviation may be as great as 15% each way.[3]

Various shape gaps with the same total air space will have different volt-time characteristics. Thus it is incorrect to talk about a "gap" unless the gap is minutely specified. Even a slight change of curvature on a gap will result in a different characteristic. This is illustrated in Fig. 3, where a certain design of double gap of 1-3/4" total air space has a higher volt-time curve than a standard two-inch rod gap.

New Transformer insulation will fail under repeated impulses at lower crest values than for one impulse. Tests have shown that such insulation will withstand about 70% of the single impulse value for a large number of shots.[4] Since three impulses reduce the impulse strength to 90% (according to the same data), and since the standard tests

require three such tests, we can take about 80% of the A.S.A. value as a conservative value for repeated shots. In addition, insulation will deteriorate with age. This is recognized by the proposed A.S.A. Standards[2], which suggest that periodic field tests should not exceed 65% of the factory tests. It is doubtful whether these two factors (the 80% and the 65%) should be applied on top of each other, but at least, to be conservative, some margin below the proved impulse level should be allowed. If we take this margin to be 40% (aged insulation strength under repeated impulse being 60% of the proved value) a volt-time curve can be drawn which will serve as a "ceiling" limit for protective devices. Such a curve is shown in Fig. 4, and was drawn by taking the lower limits of the two transformer insulation characteristics shown in Fig. 3 and applying a 60% factor. As stated before, some transformers will have much more insulation than required by the A.S.A. standards. In these cases, safety factor will have been piled upon safety factor; however, unless authoritative data can be obtained from each manufacturer, or the A.S.A. standards are raised, or unless REA specified higher impulse test requirements, there is no choice but to take the A.S.A. standards as the lower limits.

On Fig. 4 is also drawn the 2-inch standard rod gap curve. A "bird proof" double gap provided by a transformer manufacturer set 3/4-inch spacing on each gap, is not shown on Fig. 4 as it would cloud the picture; however, the curve of this particular gap follows very closely the standard 2-inch rod gap curve, but bends up faster for short times.

C. Coordination of Transformer Insulation and Protective Devices

From Fig. 4 it can be seen that for wave fronts steeper then 70 KV per microsecond, the 2-inch standard rod gap will fail to protect transformer insulation which has a strength of 60% of the A.S.A. standard for 15-KV insulation. For wave fronts of less than 70 KV per microsecond, protection is afforded, but the margin is small, and, recalling that the rod gap curve is an average of flashover tests, in some cases it would fail to afford protection even below this rate of rise. Also, referring back to Fig. 3, the cover bushing offers no protection for such insulation.

It can also be seen why a lightning protective device will furnish protection for some surges, while for others it will not. The steep wave fronts are more likely to cause damage than the more sloping fronts. The distribution line will both atenuate the crest of a surge and slope off the front (decrease the rate of rise). Hence the closer the transformer and protective device is to the initial lightning stroke, the more likely is the transformer to fail.

Data on the front of wave characteristics for surges on lines is meagre, but a 500 KV per microsecond surge is usually considered fairly severe. As can be seen from Fig. 4, a standard rod gap spacing of about 1-1/4" would be necessary with the insulation curves shown in Fig. 4 for protection on this wave front.

D. Minimum Setting of Protective Device

There are other factors which limit the minimum setting of the protective device. One of these is its 60 cycle flashover value. Faults, switching and "arcing grounds" cause overvoltages on the system which may be injurious. The maximum sustained 60 cycle voltage caused by a fault on a system depends on the values of positive and zero sequence impedances of the system. Numerous calculations for faults on multi-grounded systems such as those constructed by REA borrowers have been made, using various conductor sizes and line lengths. These calculations revealed no case where the 60 cycle voltage was over 9 KV line-to-ground for a 7.2/12.45 KV multigrounded neutral line. The transient voltages resulting from faults are somewhat higher. One authority shows that the increase is about 13% higher[5] for lines of the REA type. This would result in about 10.3 KV for the 7.2/12.45 multi-grounded system. Figure 5 shows data from 5 power systems on switching surges.[6] However, it is not known whether these systems were solidly grounded, ungrounded, or grounded through resistance and reactance.

Studies on model 110-mile 230-KV lines indicate that on solidly grounded systems, transient line-to-ground voltages caused by arcing grounds do not exceed 2 times normal; those caused by de-energizing an unfaulted line do not exceed 3.2 times normal; those caused by de-energizing the line with single line-to-ground fault do not exceed 4.5 times normal; and those caused by de-energizing the line with double line-to-ground fault do not exceed 4 times normal. All these values are for two restrikes of the arc, which would probably be unusual.[7] Also, overvoltages on such large capacitance lines would be in excess of those encountered on low voltage lines such as constructed by REA borrowers. The ceiling values given for 1 restrike for the above conditions are 2 times normal, 2.8 times normal, 2.9 times normal and 2.7 times normal, in the same order.[7]

It has been shown that a solidly grounded system almost always has lower transient overvoltages than other types of systems, while ungrounded systems have the highest, in general. The multiground neutral REA system can certainly be considered as solidly grounded.

The transient overvoltage will depend on the point on the current cycle where the transient occurs. Hence two or more maximum overvoltage values would not be likely to occur in succession.

From the above discussion, an overvoltage of about 3 times normal seems a reasonable upper ceiling for transient overvoltages on REA systems. Figure 6 shows the flashover of wet rod gaps at 60 cycle voltage.[8] The transient voltages due to switching, etc., are composed of fundamental 60 cycle components and "natural frequency" components, the natural frequency being determined by the inductance and capacitance of the circuit. This natural frequency is greater than 60 cycles and hence the flashover values will be at least as great as the 60 cycle values. From Fig. 6, using the 3 times normal figure, or 22 KV for 7.2-KV line-to-ground systems, it can be seen that a setting of 1-1/2 inches on a standard rod gap is sufficiently high to prevent transient

power flashovers. Even a 1-1/4 inch setting should be reasonably satisfactory, particularly if the line is sectionalized with automatic reclosing circuit breakers, since two or more maximum overvoltages would hardly appear in succession.

It will be noted from Figs. 3 and 4 that a 1-1/2 inch standard rod gap has characteristics for initial breakdown fairly similar to those of the 9-KV valve arrester.

In the past, some engineers have claimed that the protective device should have a fairly high initial breakdown because a higher setting would result in fewer operations, while a lower setting would result in a greater number of operations, and hence more wear and tear on the device, and more consumer complaints. There is ample data to indicate that any such difference is minute for low insulated lines having the phase wire above the neutral. Some calculations on the percent flashovers for direct strokes to be expected on lines of the REA type have been made with results as follows:

Percent Flashovers, Phase Wire Over Neutral
Direct Lightning Stroke

Insulation	Wave Front Microseconds	Positive Wave	Negative Wave
Insulator Only	1	99.0	99.0
	2	99.3	99.0
	4	99.5	99.3
Insulator Plus 2.5 Ft. Wood	1	95.0	94.5
	2	96.5	96.0
	4	97.5	97.2

If 2.5 feet of wet wood (about 175 KV on full 1-1/2 x 40 wave) makes only 2% difference in the percentage of flashovers, how much difference would 1 or 2 inches of gap make (at about 20 KV per inch on full wave)? Of course, some of the surges may be induced from nearby lightning strokes, instead of direct strokes, but even with these it is very doubtful whether an inch more or less will make much difference.

These theoretical calculations have been borne out by records obtained from REA systems equipped with reclosing oil circuit breakers. For the period from May to November 1941, the following data was gathered:

Month	Number of Systems Reporting	Number of Breakers Reported	Operations per Breaker	Transformer Protection
May	10	62	6.01	1
	23	423	4.24	2
June	17	192	9.07	1
	31	380	5.97	2
July	28	323	9.69	1
	41	662	7.60	2
August	35	405	7.93	1
	46	684	6.70	2
September	36	363	2.85	1
	47	697	6.50	2
October	18	189	2.69	1
	20	336	5.37	2

1 - Systems with arrester protected transformers

2 - Systems with open gap protected transformers

For the period from April 1 to October 1, 1942, the following data was gathered:

	Systems with Gap Protected Transformers	Systems with Arrester Protected Transformers
Number of Systems	88	99
Number of Breakers	1,314	1,141
Average Number of Operations per Breaker per Month	6.8	6.6

If the theory of a greater number of line flashovers with less insulation were accepted, a greater number of breaker operations on systems with gap protected transformers would be expected than on systems with arrester protected transformers, since arresters stop the follow current (after the first half cycle in the case of the expulsion type and immediately in the case of the valve type) and hence fewer operations should occur in the later cases.

The above breaker data, on the other hand, indicates clearly that there is very little difference in the number of breaker operations in either case. Since the number of breaker operations due to causes other than lightning are probably about the same in either case, it is reasonable to say that a small increase or decrease in

the initial flashover value of the protective device will make practically no difference in the number of operations of such device due to lightning surges.

As outlined above, the protective device setting must, of course, be kept above the possible power transient overvoltage limit. Hence from this standpoint, it would appear that a 1-1/4" gap would be about as small as could be used. Since a 1-1/2" rod gap has about the same initial flashover curve as a 9-KV valve type arrester, it would seem that an open gap having characteristics between the 1-1/4" and 1-1/2" standard rod gaps would be a reasonable gap to use.

Another important factor which may limit the gap spacing is the possibility of bird trouble and ice trouble. The lower the gap spacing, the more important it becomes to design the gap to minimize such difficulties. However, there is no reason why design problems should be insurmountable even with very short gaps. Enclosed arresters have the advantage over open gaps in respect to possible shorts from external objects, and in regard to the maintenance of proper gap spacing.

In regard to the 9-KV expulsion type arrester, it is apparent that a lowered setting would be desirable for this device.

E. Possible Increase in Transformer Insulation

It can be seen from Fig. 4 that a 1-1/2" rod gap will fail to protect the 60% of A.S.A. standard insulation for voltage rises over 154 KV/ms, allowing 15% margin each way on the rod gap curve.[3] Providing protection up to 500 KV/ms with the same margin, and with the 1-1/2" rod gap, would involve increasing the insulation strength about 25%. This in turn would mean a 138-KV flashover test at not less than 1.8 microseconds and about 120-KV full wave withstand. These values are very approximate as it is difficult to obtain accurate points for very short time lags. Although most modern transformers could probably meet such tests, since the tests are nonstandard it is probable that these transformers would be more expensive.

The REA at one time had a specification for a 1-KVA transformer calling for a test with ten impulse waves with a front of 500 KV per microsecond with a 2-3/4" standard rod gap across the transformer insulation. This is roughly a 25% more severe requirement than the A.S.A. standards, using the transformer insulation time lag shape of Fig. 4. One manufacturer quoted a price of $2.00 more for the 1-KVA transformer with this requirement than for a transformer meeting standard A.S.A. requirement. It is probable that this cost would be reduced if REA systems purchased large quantities of such transformers. Even if this were not true, any necessary cost increase would probably be well worth while.

Summarizing the above discussion for 7.2/12.45-KV transformers:

1. It appears that present double open gap settings (usually about 1" for both air spaces) are higher than they should be for adequate conservative transformer protection over long periods.

2. A gap setting having flashover characteristics between the 1-1/4" and 1-1/2" standard rod gap will provide much better protection and still not increase the number of flashovers appreciably.

3. As each gap has individual characteristics determined by its shape and mounting, it would be necessary to test each to determine accurately the setting corresponding to that suggested in 2. Very roughly, for a double gap the total air space should be about 1 inch, since a double gap has a higher flashover in general than the standard rod gap. It might be necessary to check on the 60-cycle flashover value in some cases. It certainly will be necessary to make sure that any decrease in gap spacing does not increase the possible hazzard due to birds, ice or foreign objects to an unreasonable extent.

4. It would seem desirable to lower the initial flashover characteristics of the 9-KV expulsion type arrester if it is possible to accomplish this without materially decreasing the arrester life.

5. It would seem desirable to increase the required insulation impulse tests on transformer insulation about 25% to obtain more complete protection. This increase in insulation seems to be necessary because the initial breakdown of the protective device cannot be lowered materially below 50-KV on 1-1/4 x 40 full wave without at the same time approaching a lower limit imposed by transient power flashovers. (This would not be so true for entirely enclosed arresters which are protected from the weather.)

III. Protection Against Overloads and Short Circuits

A. Primary Protection

In the first few years of the REA program, the largest number of transformer installations were those called "the conventional." This consisted of a transformer, primary fused cut-out and lightning arrester. Originally the 1-1/2 and 3-KVA units were fused with 1-amp. fuse links, the smallest generally available. So many transformer cut-out fuse failures were caused by lightning and mechanical vibration, that the fuse rating was generally changed to 2 amperes. Some systems even went further than this and applied higher ratings.

Fuse links made by different manufacturers vary greatly in time-current characteristics, but in general a 2-amp. fuse will afford little protection against secondary faults on a 1-1/2 or a 3-KVA transformer, particularly if these transformers are connected for three-wire service. (Primary protection against long time overloads by means of overcurrent devices is not practicable and has largely

been abandoned by most electric suppliers.) Unless the secondary short circuit is very close to the transformer, the transformer will fail before the 2-amp. primary fuse will blow.[10] A 1-1/2 KVA 3-wire transformer is protected against secondary short circuits by a 2-amp. fuse of only one make - and this for a distance of only 70 feet for #8 wire. The 3-KVA is, of course, better protected. Even with the 2-amp. external fuse, there are a considerable number of fuse failures due to lightning and mechanical difficulties.

After learning of these facts, REA engineers naturally asked, "Why spend money on something which fails to protect? Why not put the fuse inside the transformer and make it large enough so it will operate only when the transformer itself fails and eliminate the expensive external cut-out?" Such transformers have been installed. The internal fuse, which was under oil, saved about $8 over the conventional installation, and was called by some a "weak link." Since it was not readily replaceable, its only purpose was to disconnect the transformer from the line in event of transformer failure. Practically, this usually meant an increase in the size of the primary fuse over that formerly used in the external cut-out. Except in rare cases, this solved the lightning and mechanical problem, but it raised another problem - namely coordination of the weak link with the primary line sectionalizing apparatus.

If a transformer fails, it is extremely desirable to automatically disconnect it from the line before the line sectionalizing device opens the entire line section. Since the weak link was larger than the external fuse on the conventional installation, it became more difficult to accomplish this, particularly out on the ends of the system. The situation was worse where fast-opening automatic oil circuit breakers were used, since the smaller breakers many times locked out before the weak link disconnected the transformer. In such event, the hunt for the offending transformer might require a great amount of consumer hours outage time on the section.

B. Secondary Protection

Some of the weak link transformers were not equipped with a secondary protective device of some sort, while some were. For the former type (not equipped with secondary protection) the usual practice has been to make the weak link or internal fuse so large that it will not operate except for internal transformer fault. This was done to prevent internal fuse blowing due to secondary faults, since it is almost impossible to replace an internal fuse without bringing the transformer into the shop.

For the transformer with secondary protection, the internal fuse must be only large enough to coordinate properly with the secondary protective device. Consequently, the internal fuse for the former type must be greater in size than for the later type. This is illustrated by the following table of internal fuse or weak link ratings for one manufacturer's equipment.

Transformer Size KVA	Internal Fuse Rating: Without Secondary Protection	Internal Fuse Rating: With Secondary Protection
1-1/2	8	5
3	15	8
5	20	8
7-1/2	30	15
10	40	15

(These ratings are with the fuse under oil and do not correspond to fuse ratings in air.)

The internally fused transformer with secondary protection will therefore be more likely to clear the line than the transformer without secondary protection. Also, of course, we would expect fewer transformer failures with the secondary protection.

C. Possible Solutions to Short Circuit Protection Problems

Various lines of thought have come up leading to a possible solution to these problems. Some of these are:

(1) Development of an external primary fuse or device which will not blow due to surges, and will be mechanically strong, but will afford protection to the transformer against secondary faults.

(2) Use of secondary protection on all internally fused transformers, making the internal fuse as small as possible.

(3) Making the internal fuse more easily replaceable.

(4) Incorporation of greater time delay in opening for sectionalizing circuit breakers. There is an upper limit to the extent of the time delay, but new breakers are now being developed with such time delay.

(5) Development of new inexpensive devices for use in conjunction with the automatic reclosing breaker so that smaller sections of line will be isolated when trouble occurs. One idea is to use a reclosing circuit breaker with instantaneous first opening and time delay subsequent opening in conjunction with single shot fuses.

(6) Development of some sort of indicator on the transformer to indicate when it has failed.

Of these items, 2, 4 and 5 together are probably the most practical. It is particularly suggested that wherever an internally fused transformer is used, it be equipped with secondary protection.

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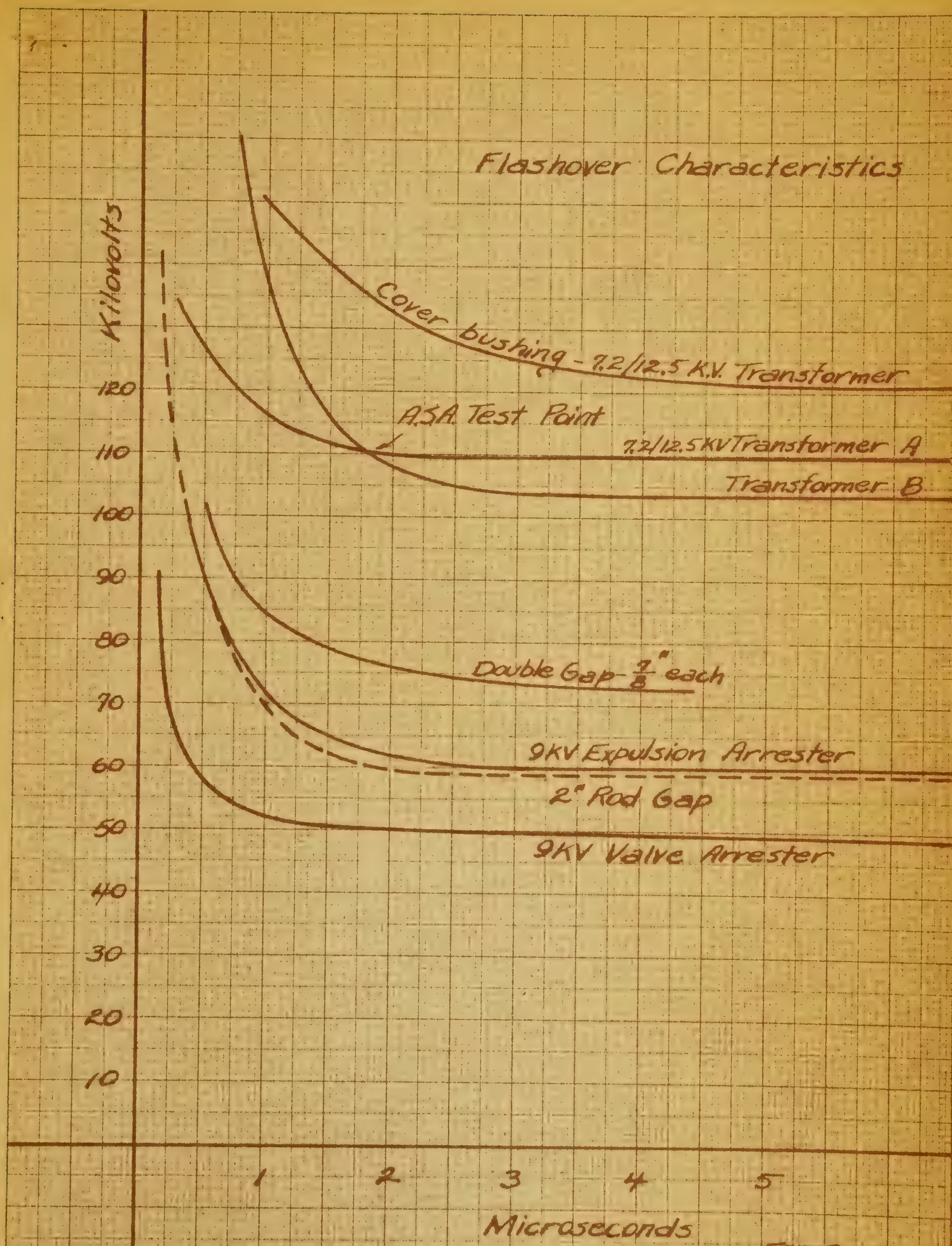
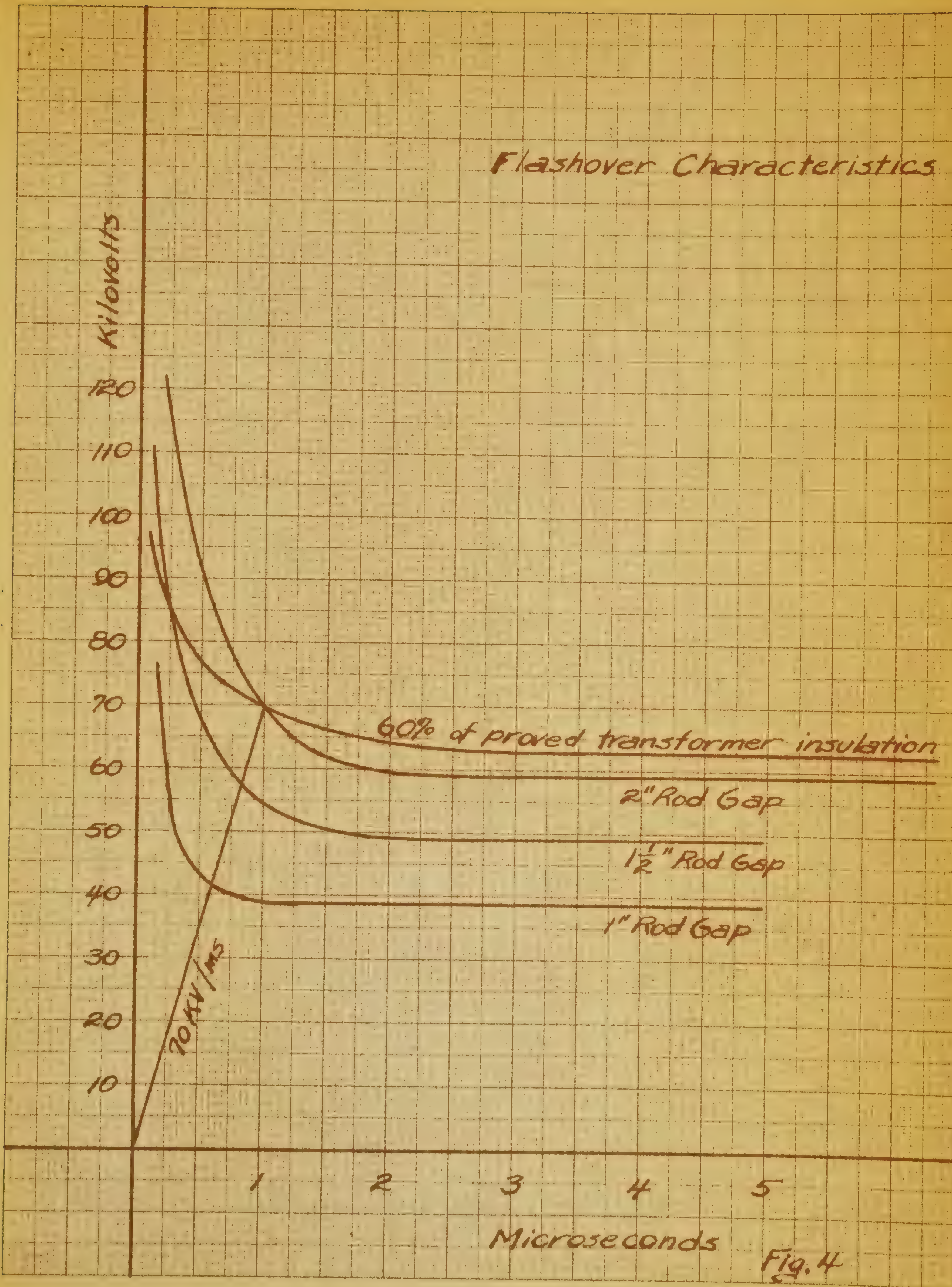
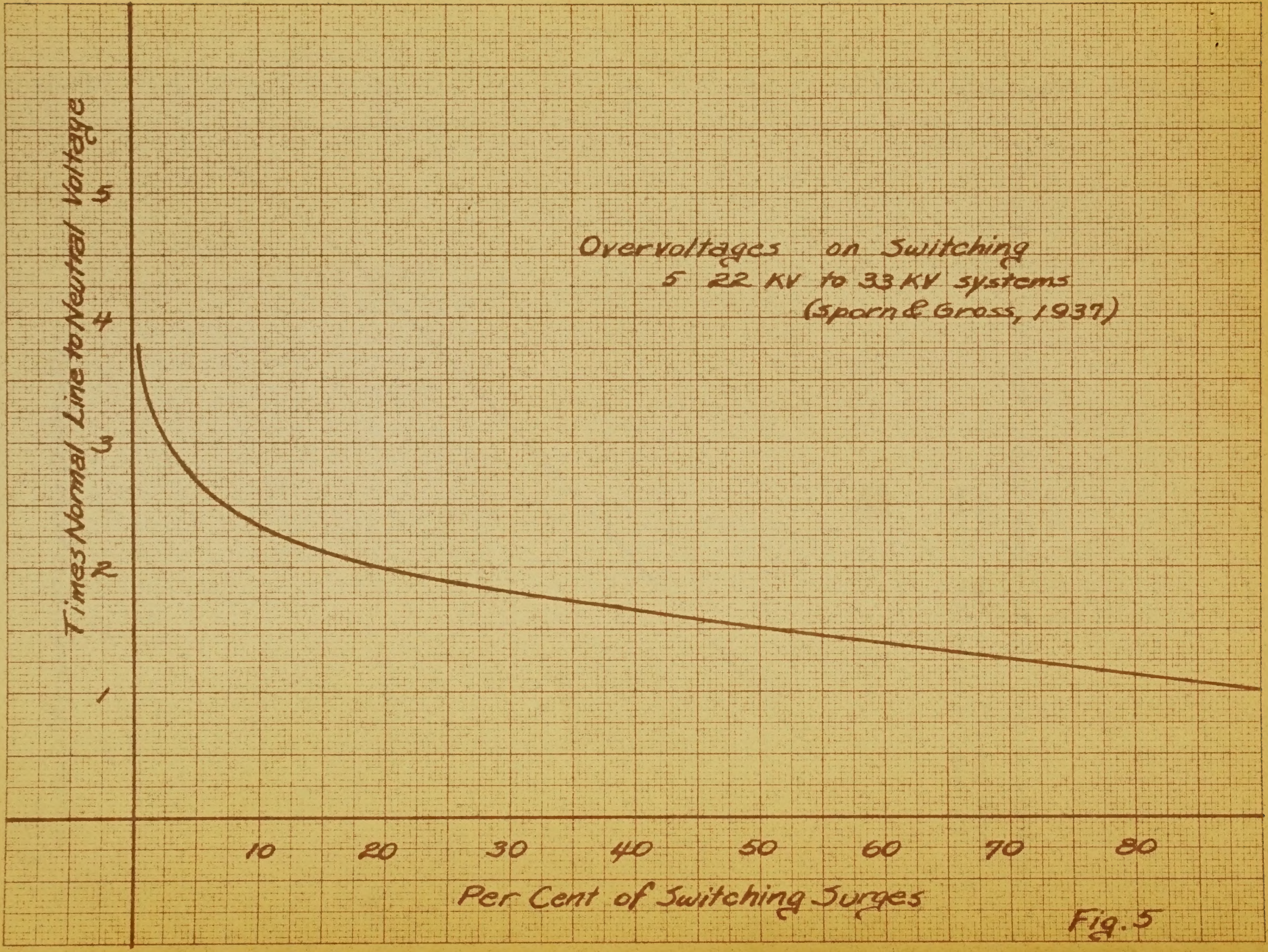


Flashover Characteristics
Kilovolts
120
110
100
90
80
70
60
50
40
30
20
10
Cover bushing - 7.2/12.5 K.V. Transformer
A.S.A. Test Point
7.2/12.5 KV Transformer A
Transformer B
Double Gap - 7/8" each
9KV Expulsion Arrester
2" Rod Gap
9KV Valve Arrester
1
2
3
4
5
Microseconds

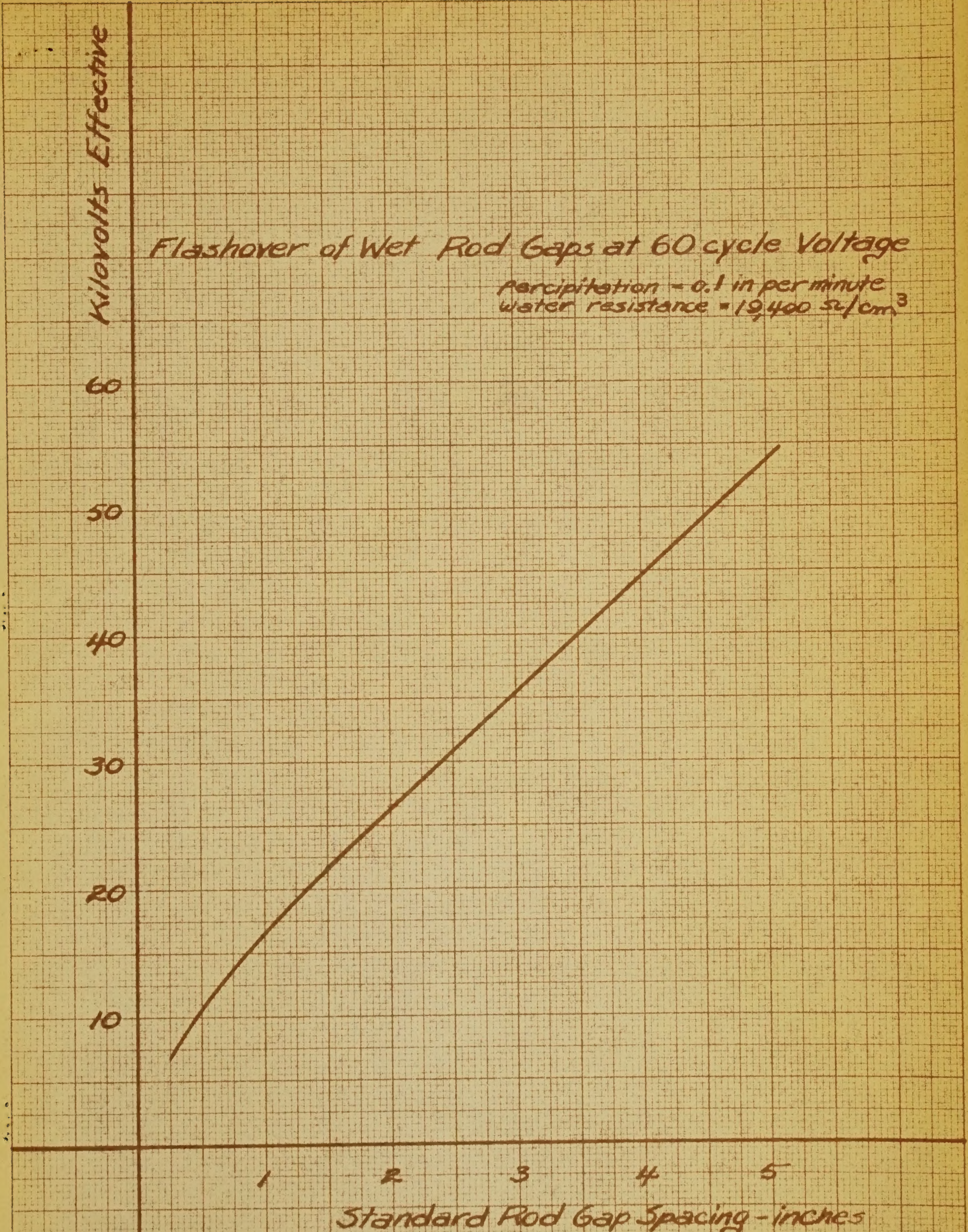
Fig. 3.


Flashover Characteristics
Kilovolts
120
110
100
90
80
70
60
50
40
30
20
10
60% of proved transformer insulation
2" Rod Gap
1½" Rod Gap
1" Rod Gap
70 KV/ms
1
2
3
4
5
Microseconds
Fig. 4



Overvoltages on Switching
5 22 KV to 33 KV systems
(Sporn & Gross, 1937)
Times Normal Line to Neutral Voltage
1
2
3
4
5
10
20
30
40
50
60
70
80
Per Cent of Switching Surges

Fig. 5



Flashover of Wet Rod Gaps at 60 cycle Voltage
Percipitation = 0.1 in per minute
water resistance = 19,400 Ω/cm³
Kilovolts Effective
60
50
40
30
20
10
1
2
3
4
5
Standard Rod Gap Spacing - inches

Fig. 6